

Friction Stir Welding of Aluminum and Titanium alloys

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Report Documentation Page

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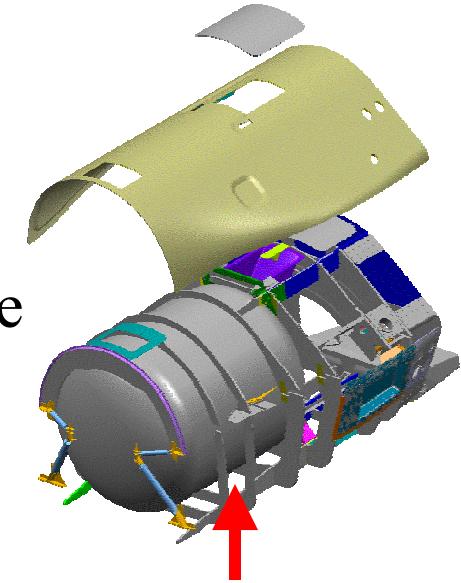
Friction Stir Welding and Processing

- Friction stir welding will offer structural assemblies with high efficiency (Performance)
 - Examples: Through lowering of weight by elimination of fasteners
 - (Large cargo aircraft have approximately 1,000,000 fasteners)
- Many calculations show that cost (Affordability) will be lower with FSW once initial equipment is purchased
- Friction stir processing offers a route to
 - Superplastic forming
 - Elimination of cast microstructure and casting defects



Why is USAF doing this work?

- Replace fusion welding for Reusable Launch Vehicles and Next Generation Launch Technology
 - Current fusion welding methods are inadequate
 - Property loss with each repair
- Aging aircraft applications
 - Corrosion at fasteners
 - \$1B corrosion costs just for Air Force
- Future Aircraft
 - Unitized Structures
 - Components of UCAV





Background

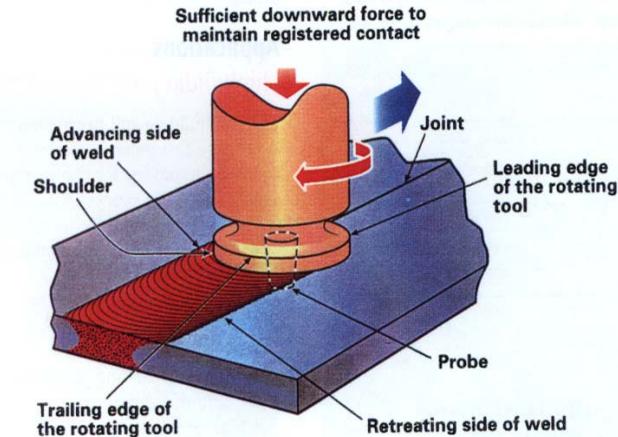
- FSW was invented at TWI (Cambridge) in 1991 and patented in 1992. Now in use and under study world wide
- Process is well established for Al alloys in a wide range of thickness
- Proof of concept demonstrated for steel and Ti but not in commercial use yet



Key Process Variables

•Process Control

- Z-axis force-the forging force normal to the plate
- Tool rotation rate
- Welding speed.
- Lead angle-tool tilt relative to the plate (0°-3°)



•Process response

- X-axis force: opposing tool motion
- Y-axis force: perpendicular to tool motion in the plane of the plate
- Torque (power)

•Other

- Plate thickness (1mm-75 mm, depending on material).
- Plate composition (flow properties).
- Tool geometry (shoulder and pin).

Good welds may be made with large variation in any or all of these variables; however, the best* weld requires careful choice.



Typical FSW Tools



Tools for conventional welding of al-alloys



3-piece self-reacting tool

W-Re tool in collet-style tool holder.
Used for welding steels and Ti alloys

Shoulder
25 mm ϕ



Pin
10 mm ϕ

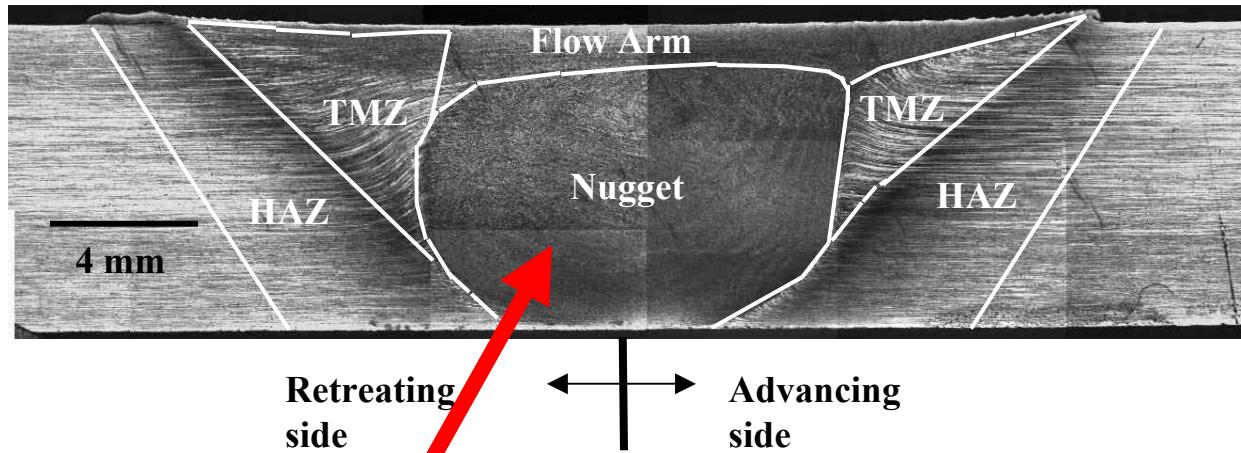
CBN tool for welding steel sheet





FSW Terminology

Microstructure



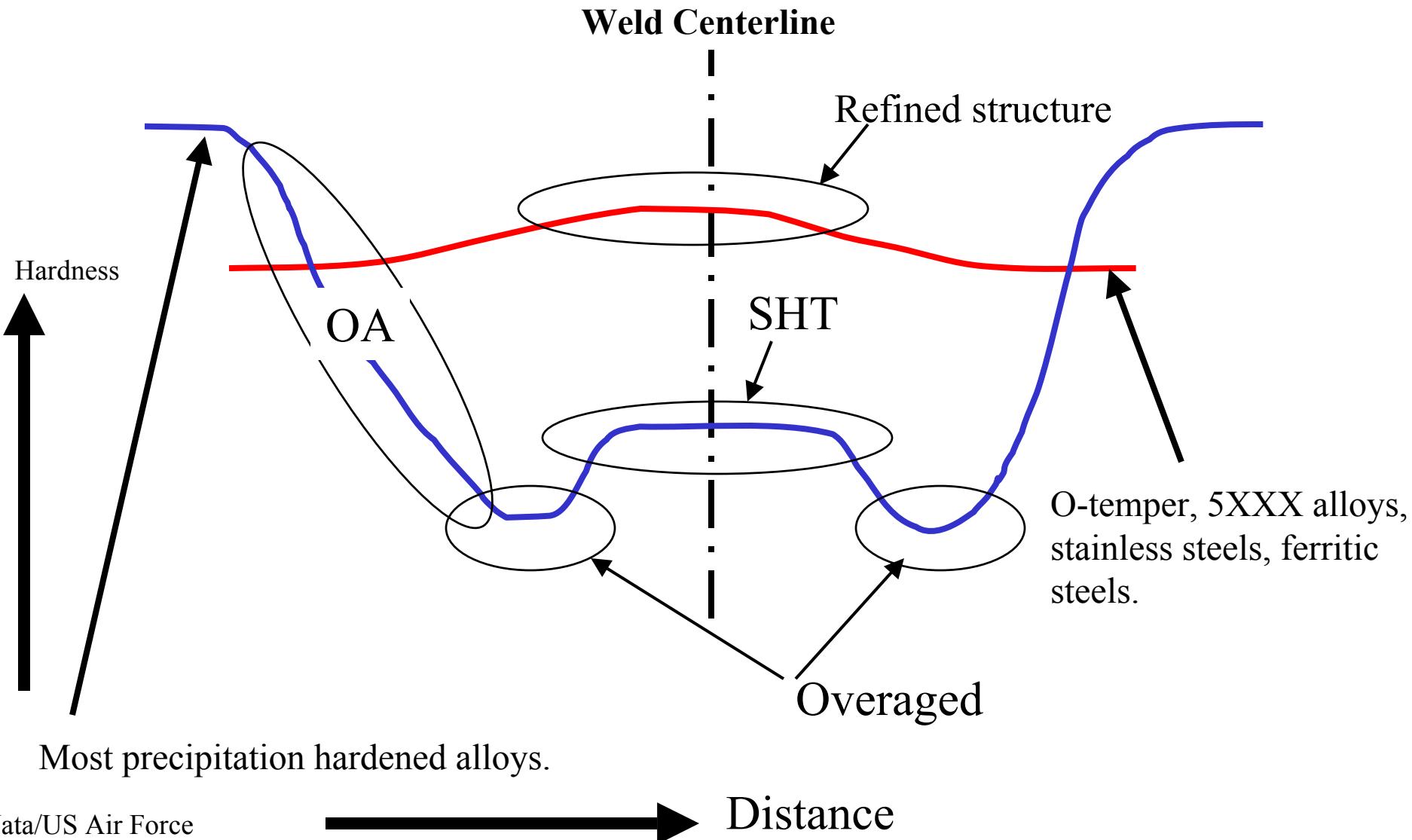
No solidification structure or defects and max T may be considerably below the solidus.

Dynamically recrystallized zone (Jata & Semiatin: Scripta Materialia, 2001)
Superplastic formable (Reynolds: Materials Science & Engineering, 2003)



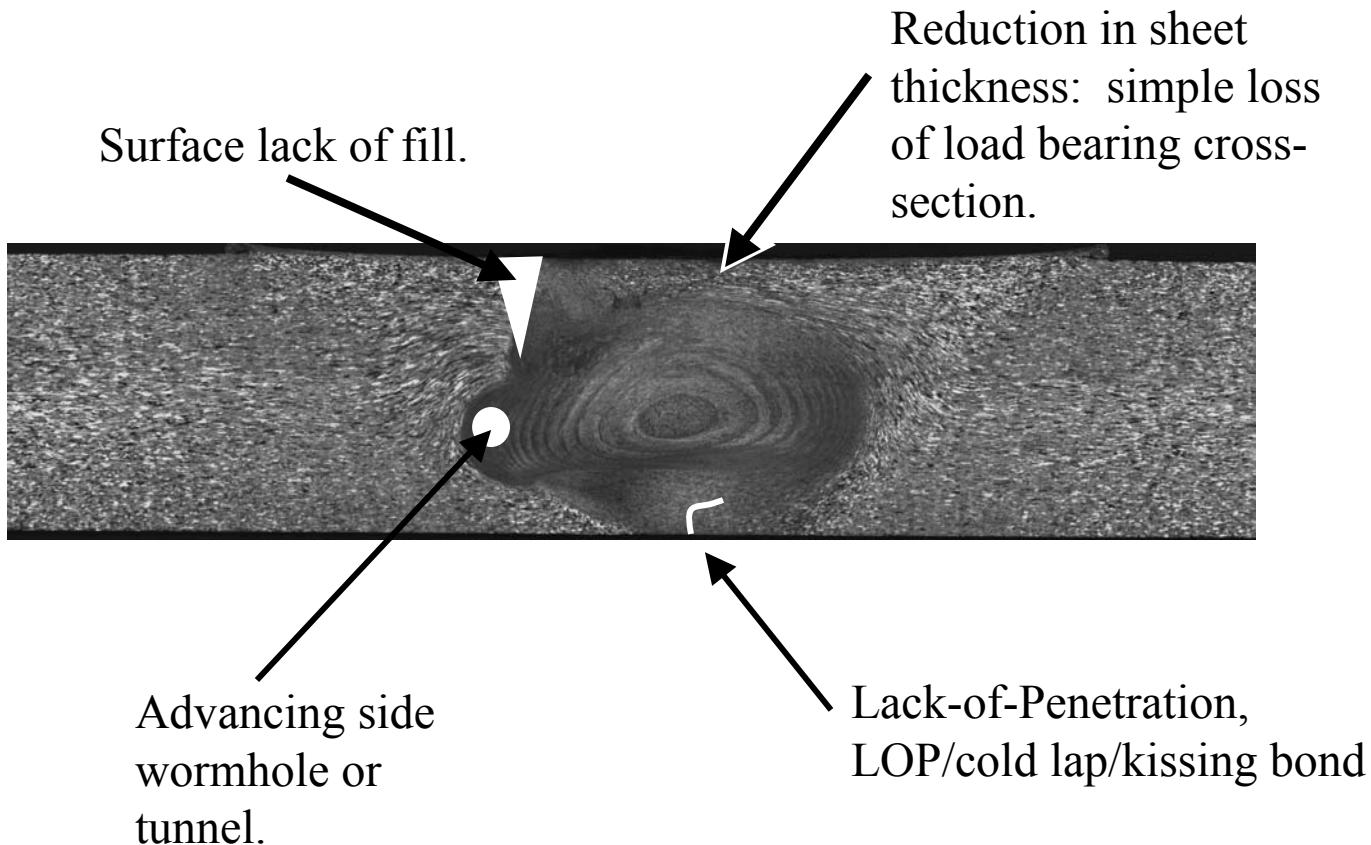
Typical Hardness Profiles after FSW

Schematic for Al alloys



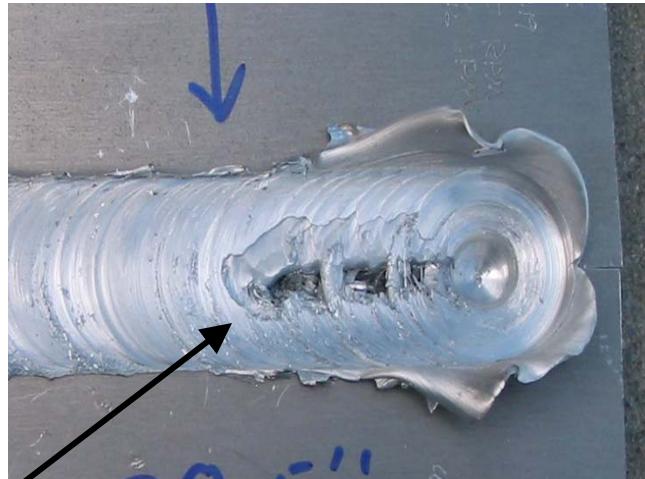


FSW Defects (un-)Commonly Encountered





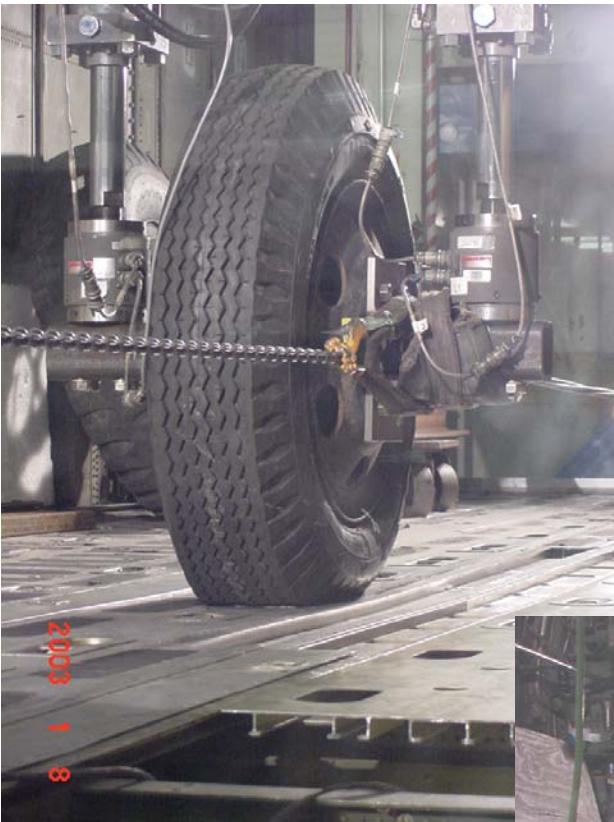
Wormhole Defect Production



- Weld, $\approx 0.67\text{m}$ long in 2219, 9 mm thick plate.
- 1.7 mm/s welding speed.
- rpm varying continuously from 90-900.
- Advancing side defects observed at very high and very low advance per revolution (low and high RPM).



FSW is being applied to A/C



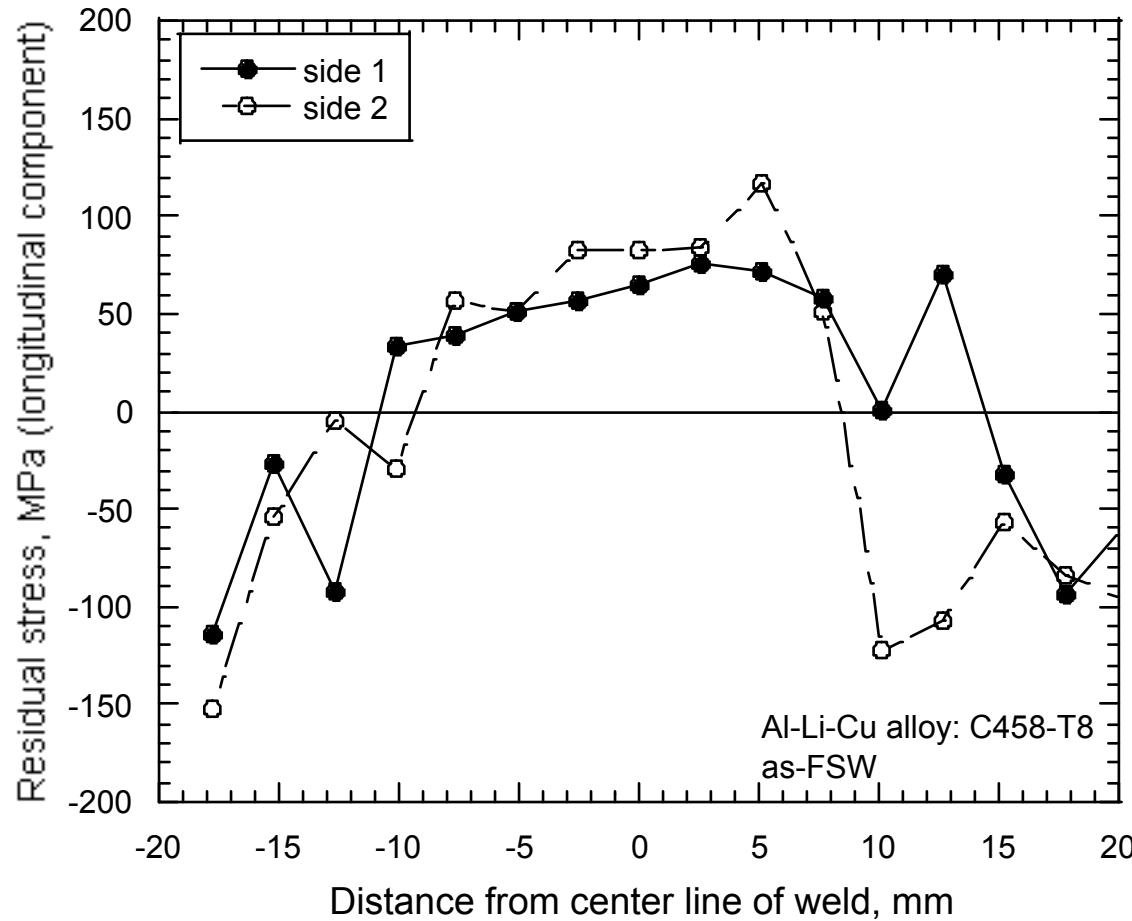
*Large Cargo A/C floor
Corrosion needs to be proven*



Low residual stresses in FSW

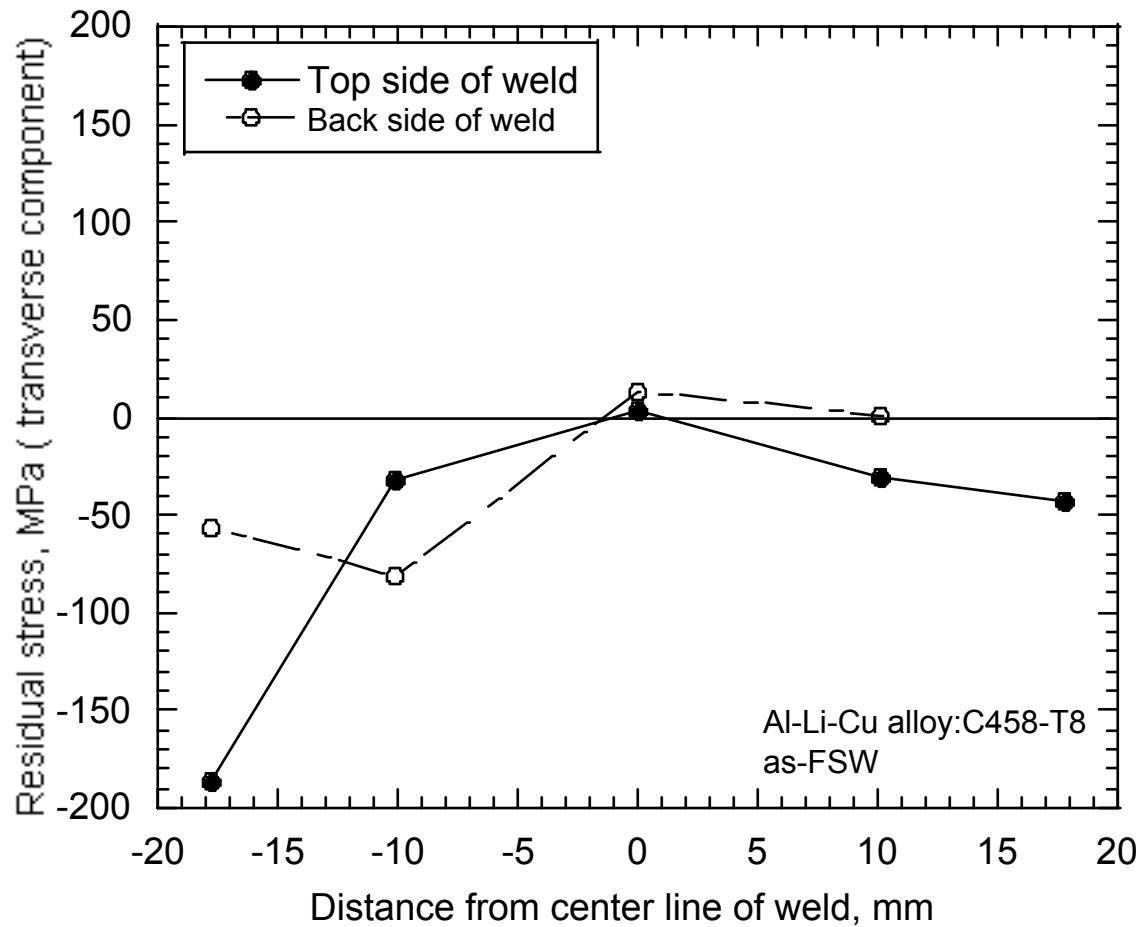
X-Rays

CT Coupons



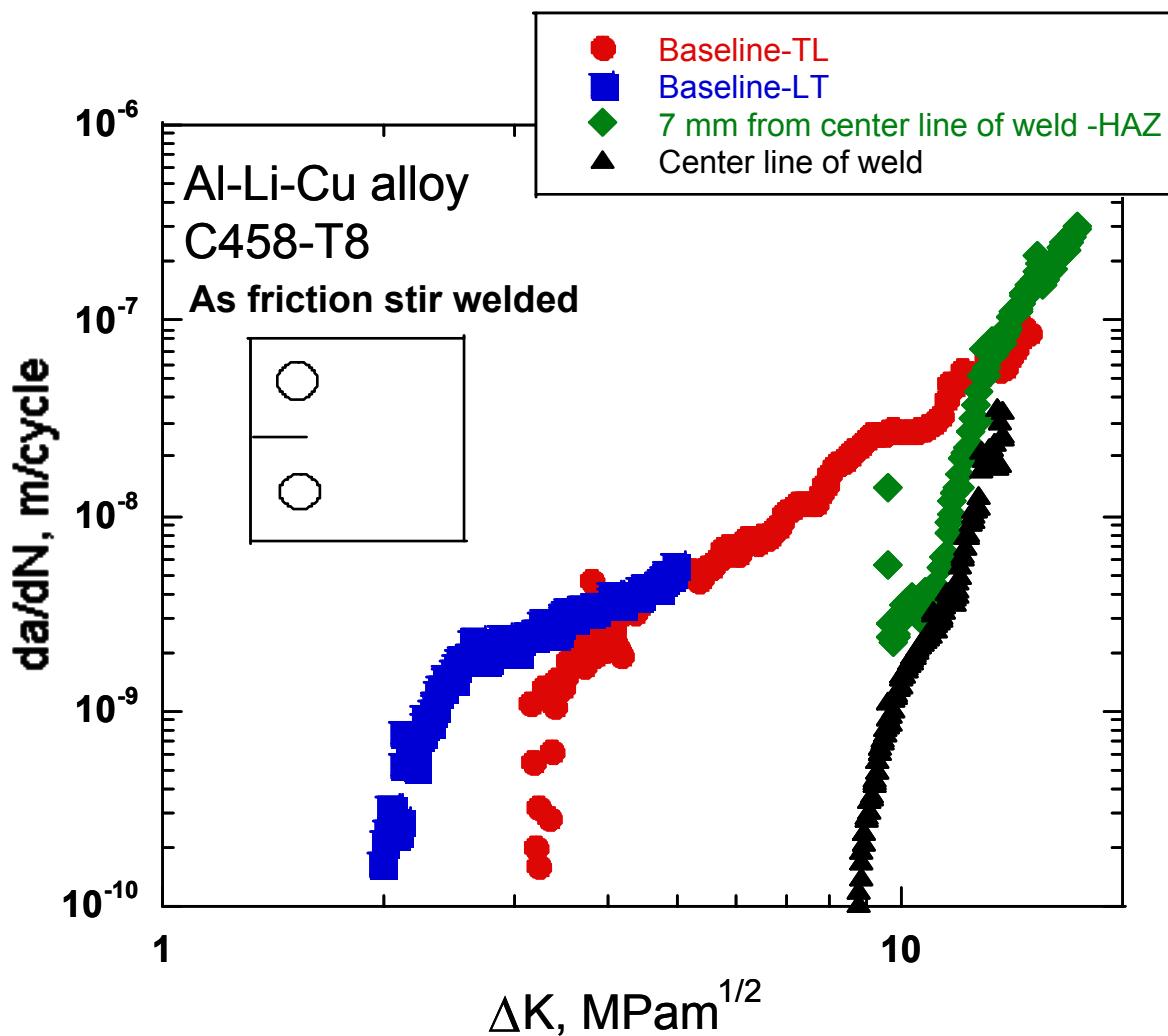


Low residual stresses in FSW



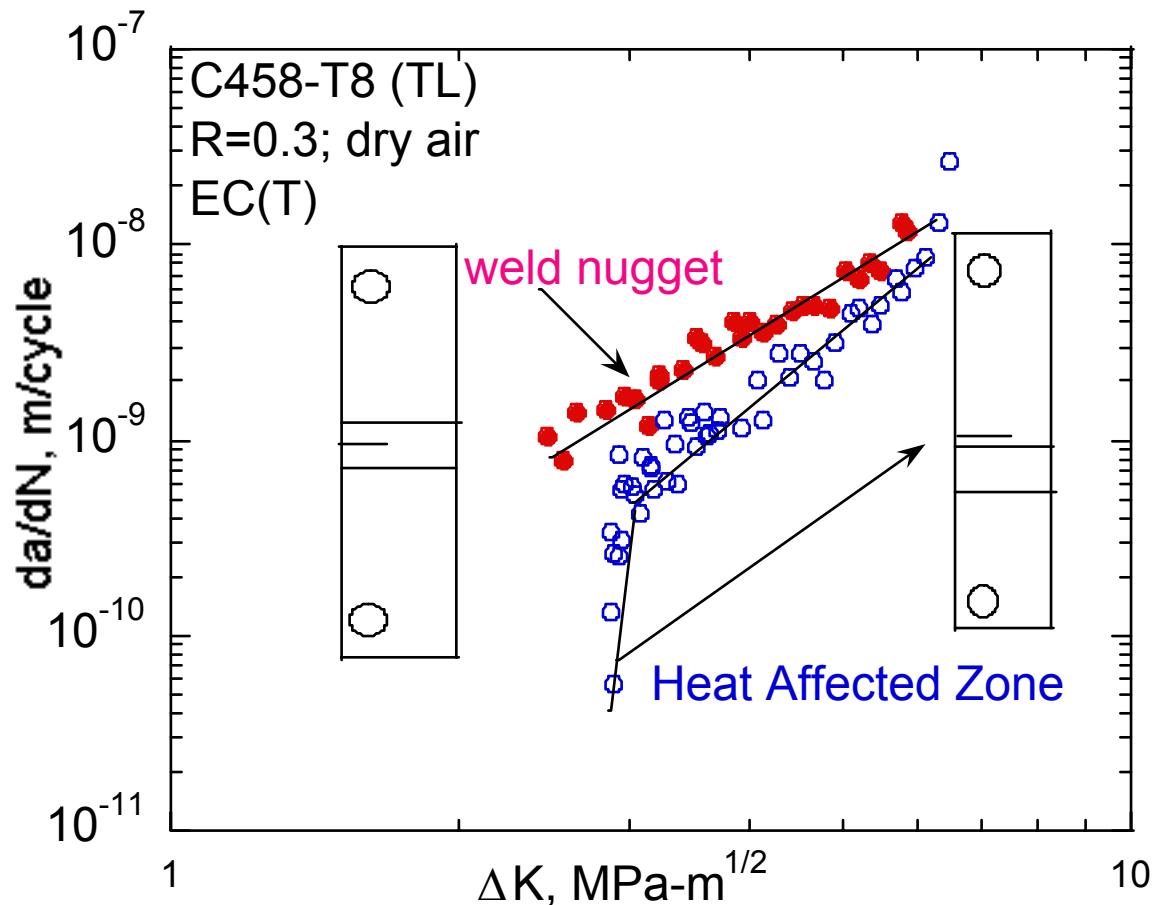


Fatigue crack growth in Al-Li alloy C458



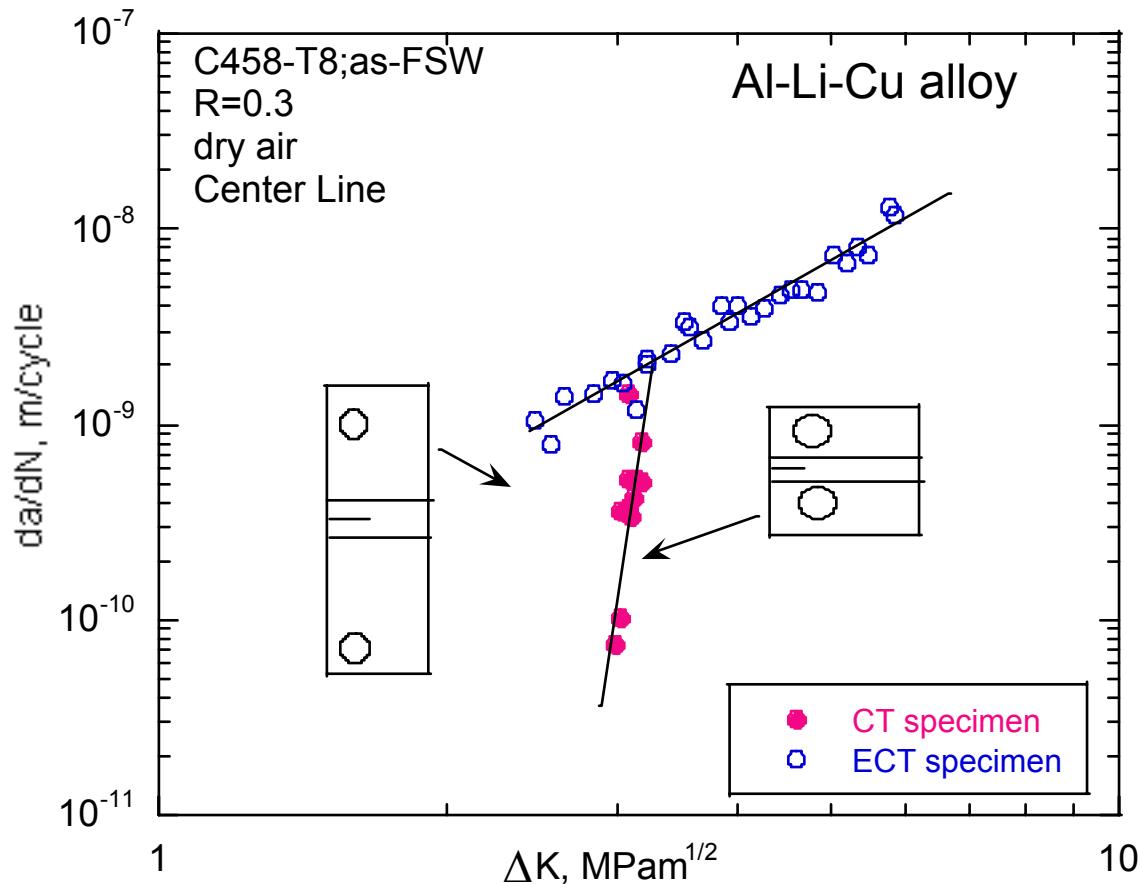


Fatigue in the weld; Nugget vs. HAZ





Effect of specimen geometry on FCG ?





Ti alloys

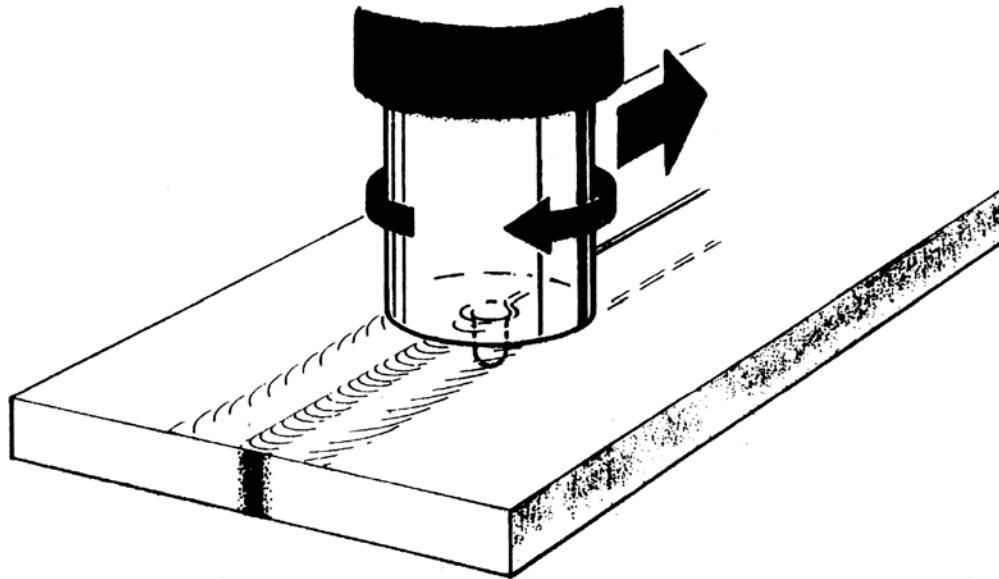


Joining Considerations for Ti

- Joining of Ti alloys is complicated by their high reactivity and low thermal diffusivity
- Embrittlement resulting from the absorption of interstitial elements (O, N, and H)
- Formation of porosity in fusion welds
- Strong dependence of microstructure and properties on processing history



Joining Considerations for Ti



- Solid-state process eliminates problems associated with melting and resolidification.
- Uses cylindrical tool with cylindrical pin extending from shoulder.
- Tool is rotated to desired RPM and plunged into joint.
- After short dwell time, tool is traversed along joint.
- At end of joint, tool is lifted and rotation is stopped.

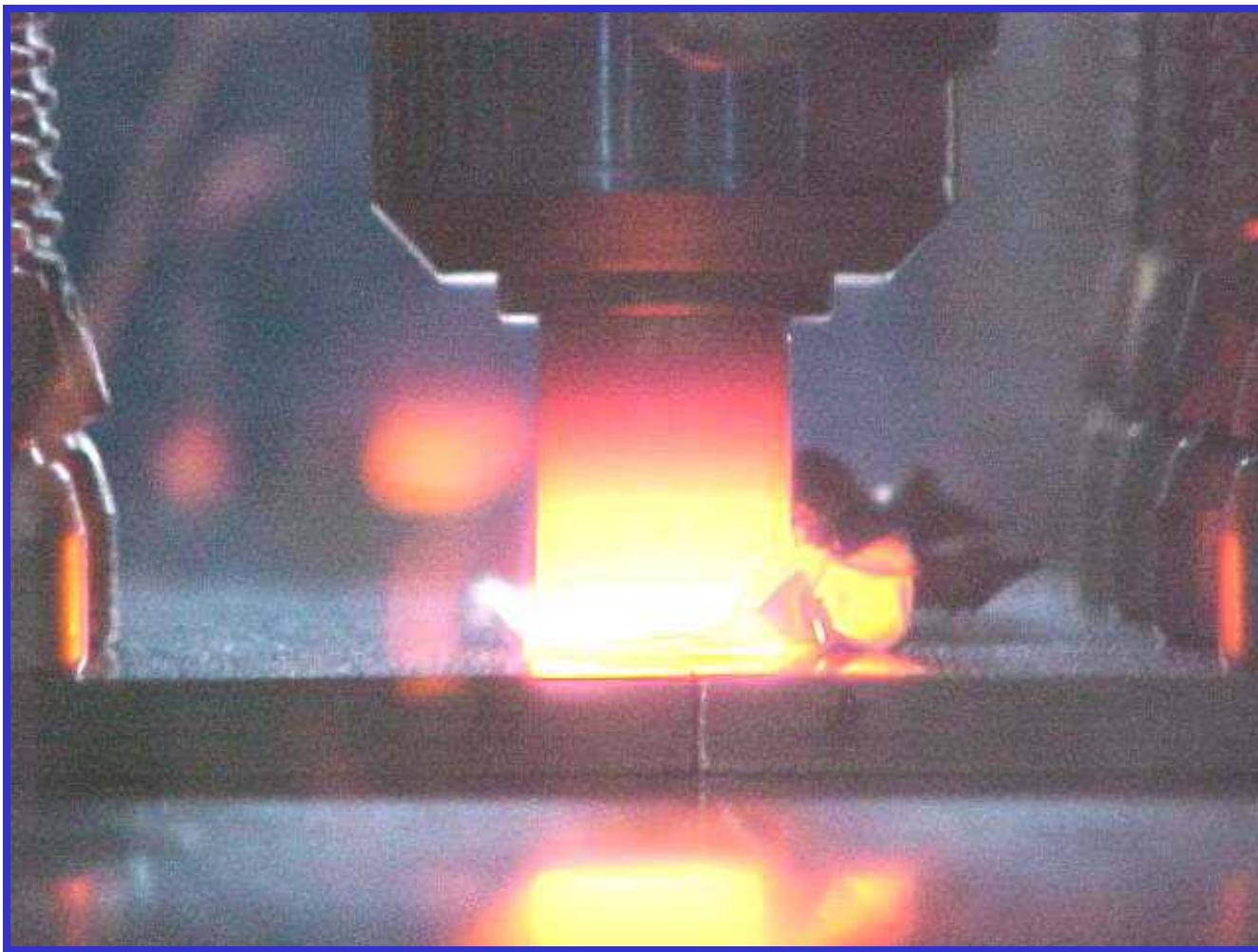


Experimental Procedures

- ~ 1/4" (~6mm) Ti-6Al-4V plate in mill annealed condition
- FSW at 4 ipm (100 mm/min) using inert gas shroud
- Optical microscopy: Etch with 3% HF & 10% H_2O_2 in water.
- Microhardness testing: 1 kg load & 15 seconds dwell time.
- Bend testing and transverse tensile testing at room temperature

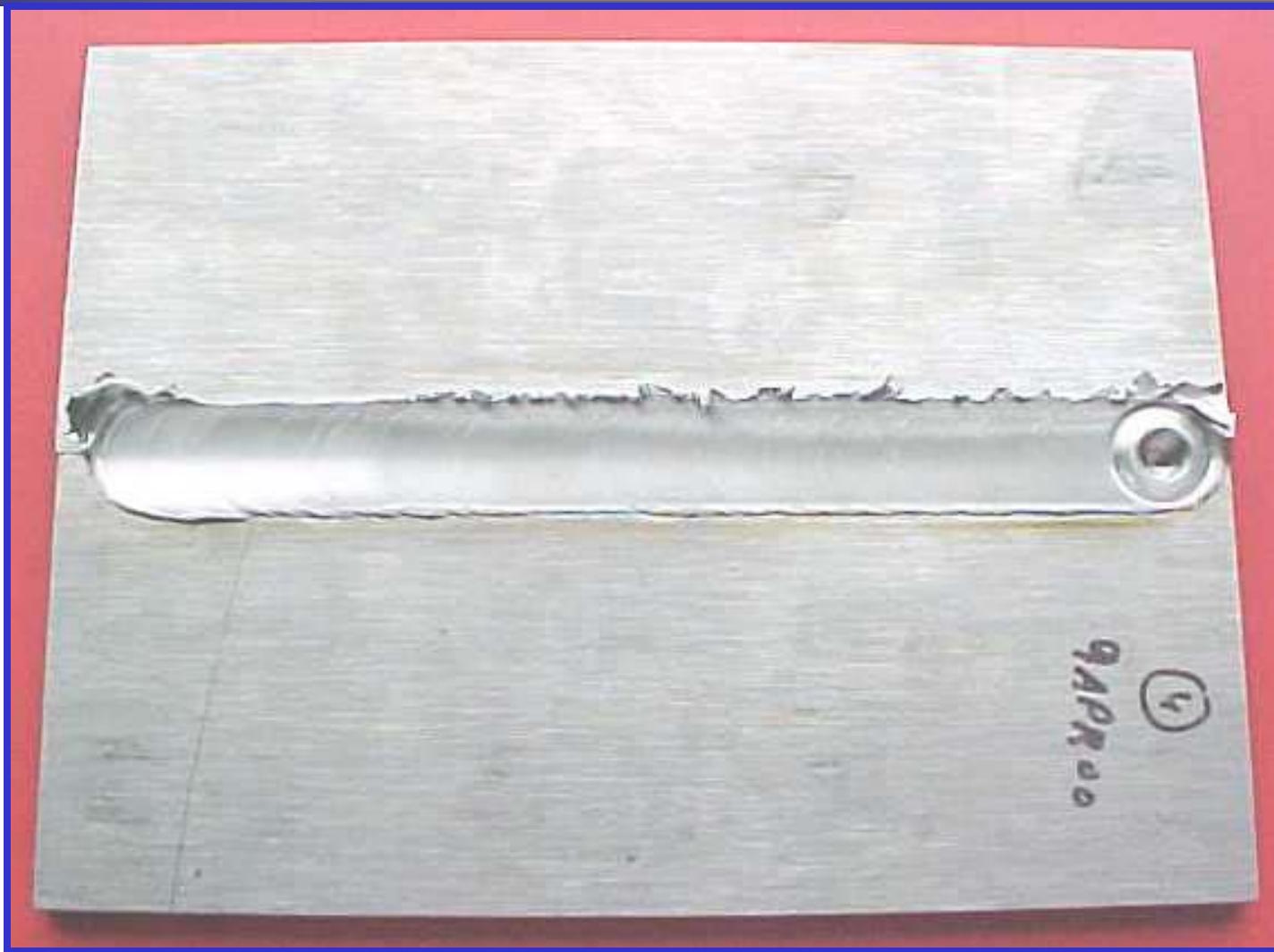


FSW of Ti- 6Al- 4V



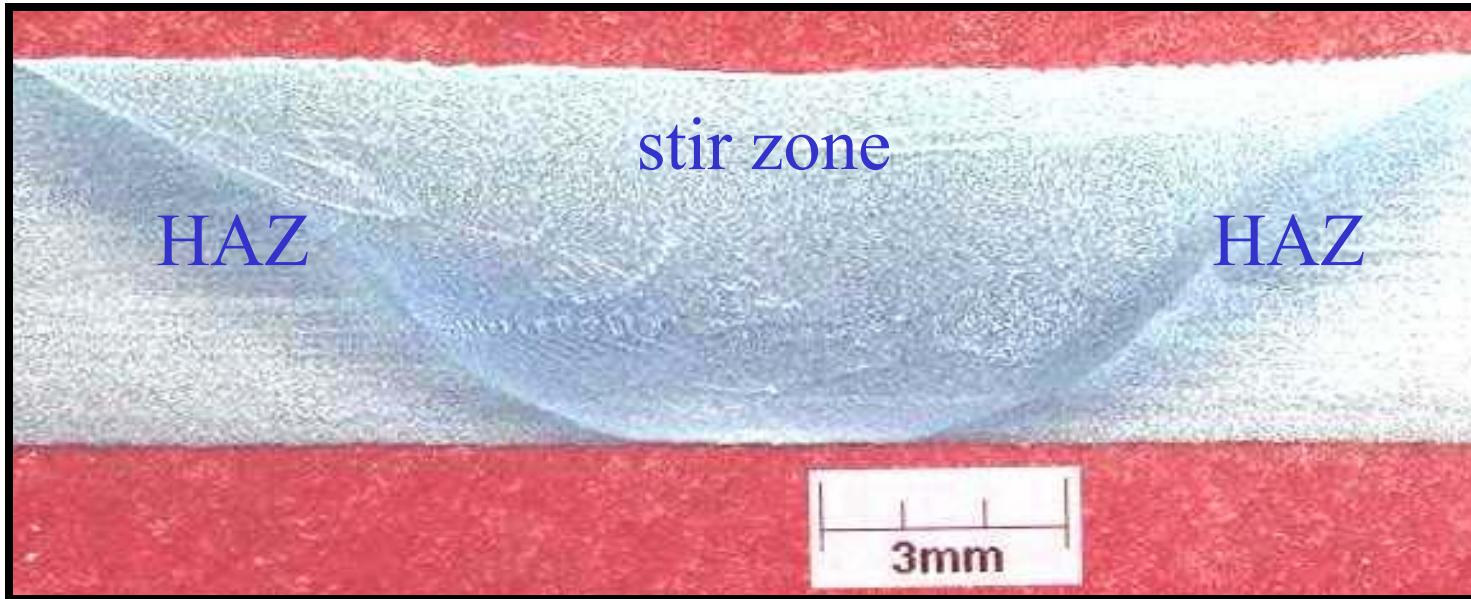


Top View of the FSW Butt Joint





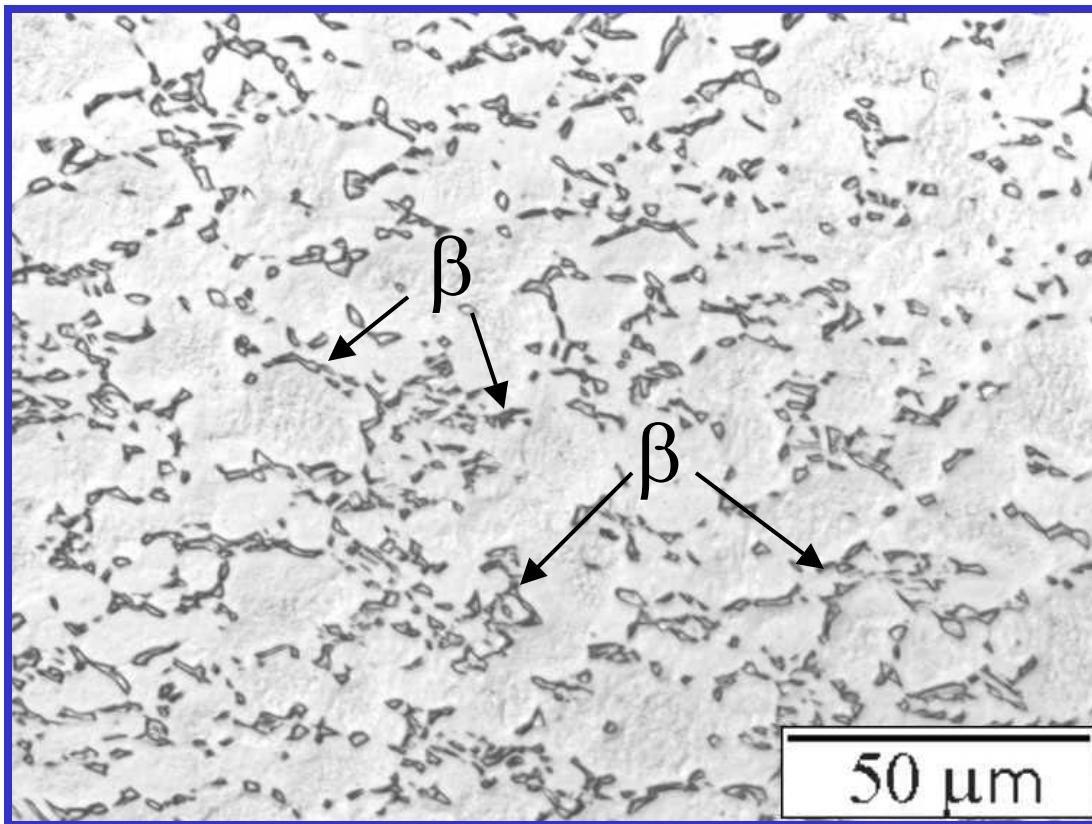
Optical Macrograph



**Transverse cross-section of
FSW on Ti-6Al-4V**



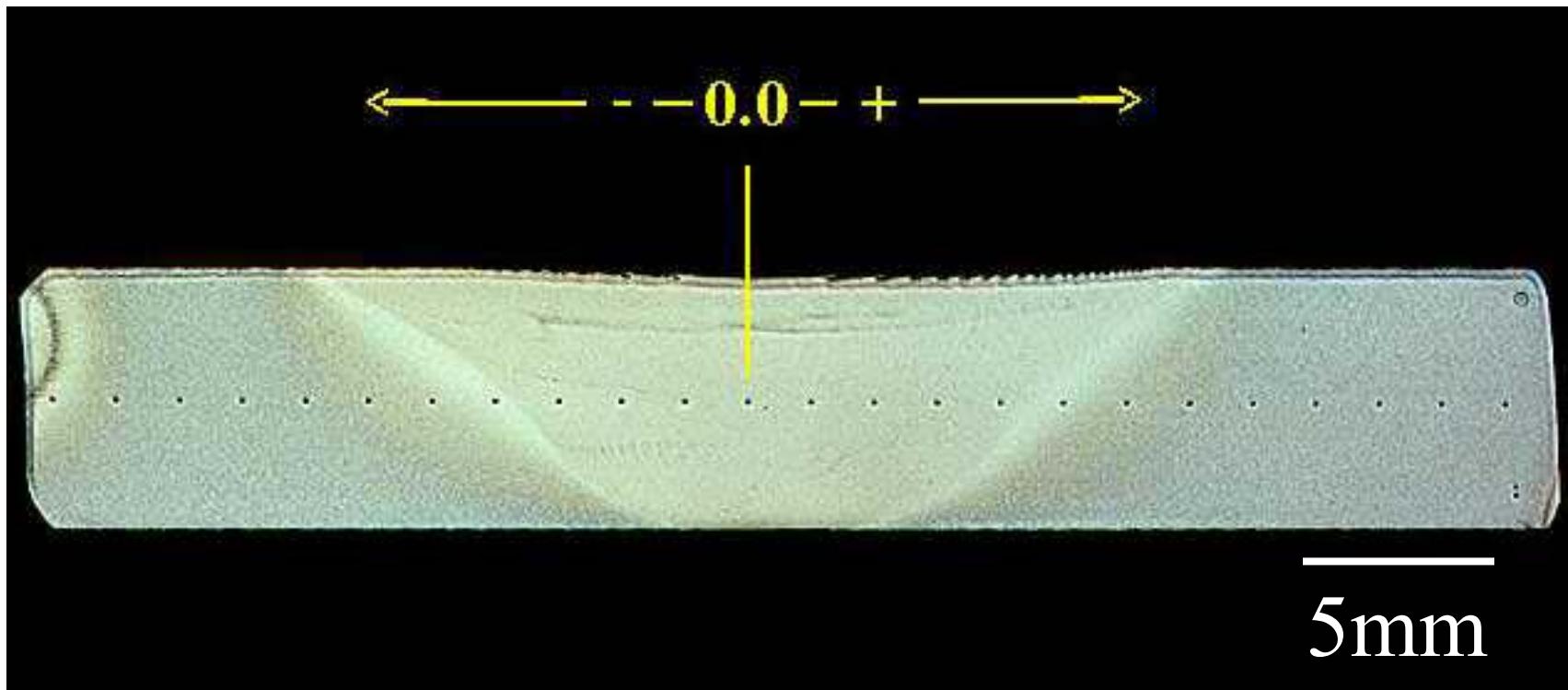
Optical Microscopy



**Ti-6Al-4V Base Metal:
mill annealed condition**

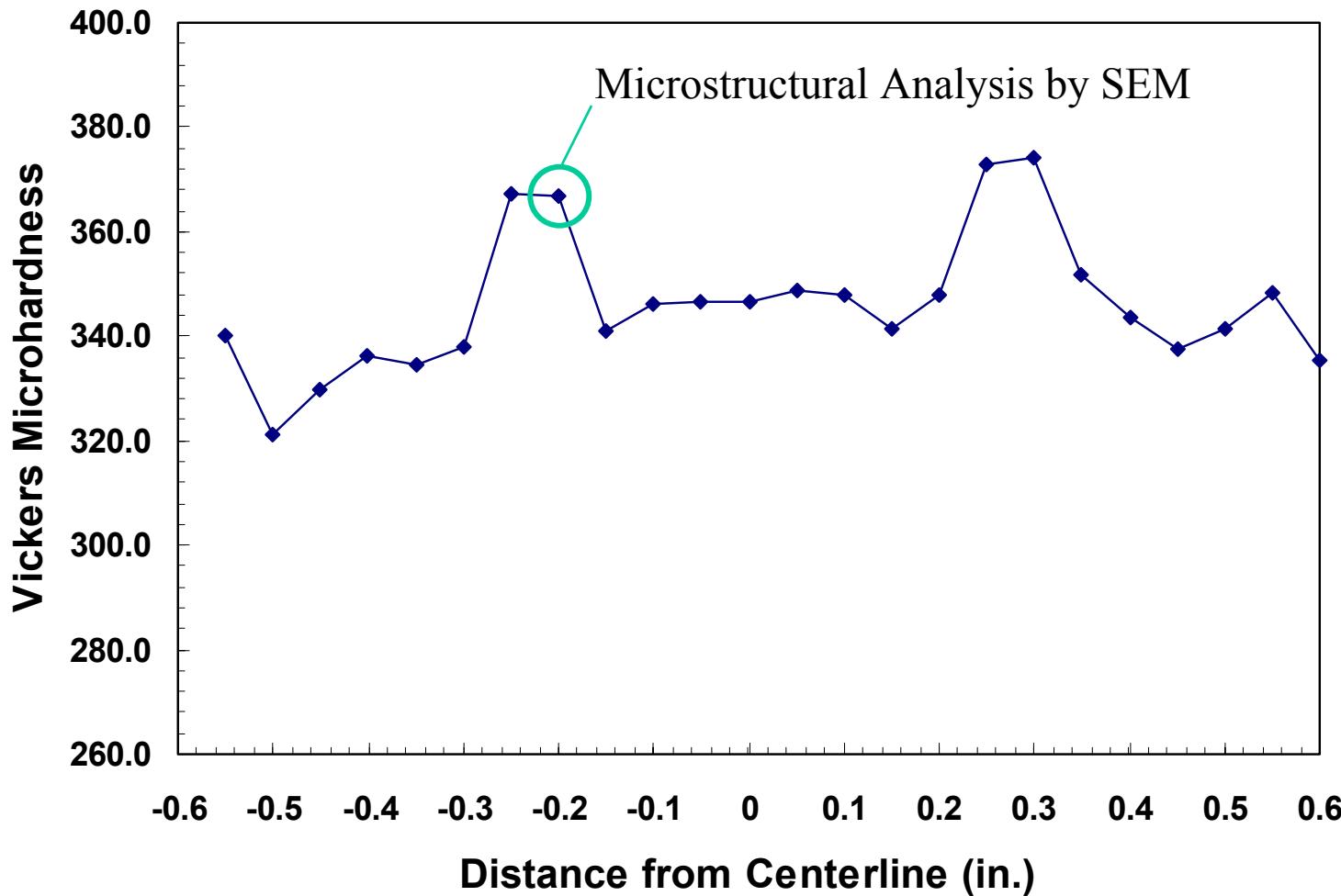


Microhardness Indentations



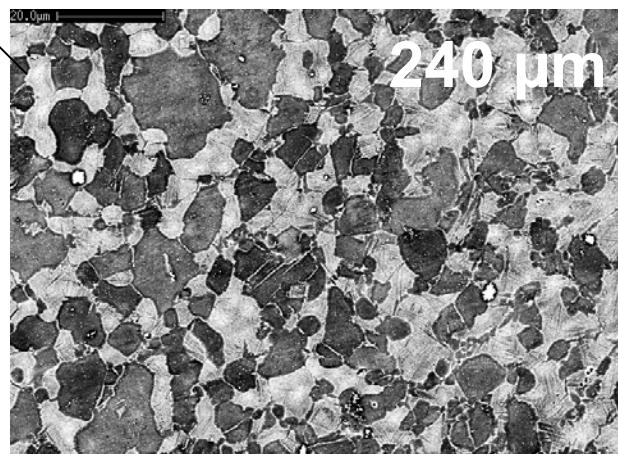
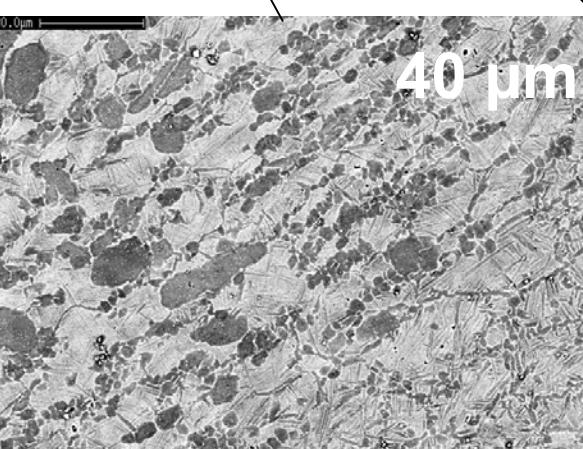
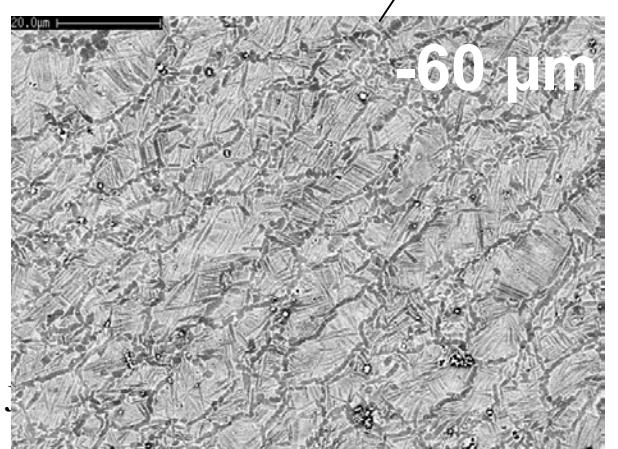
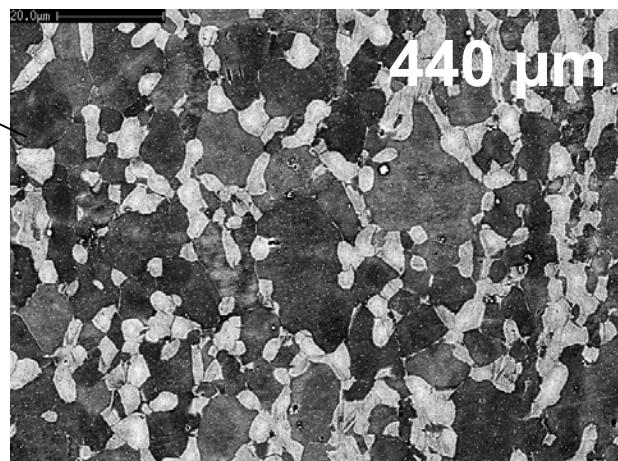
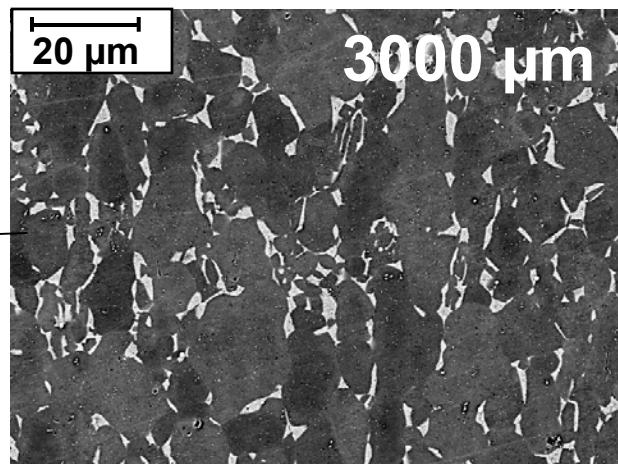
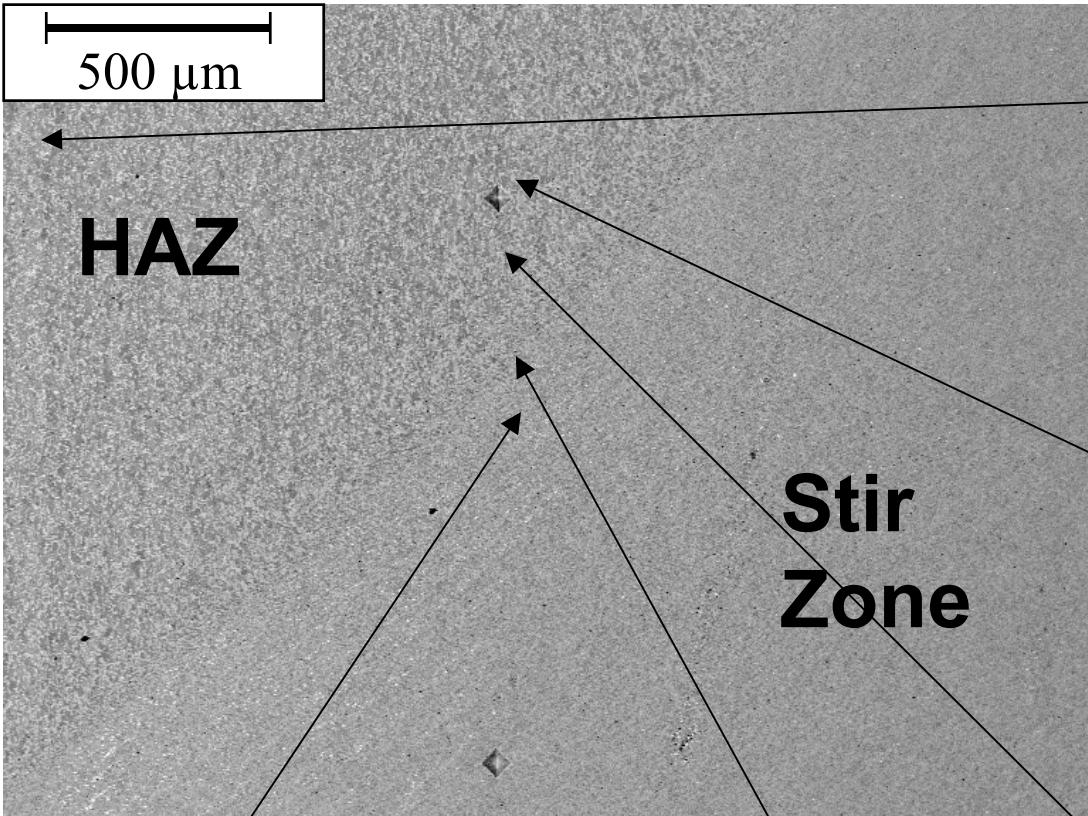


Microhardness Test Results



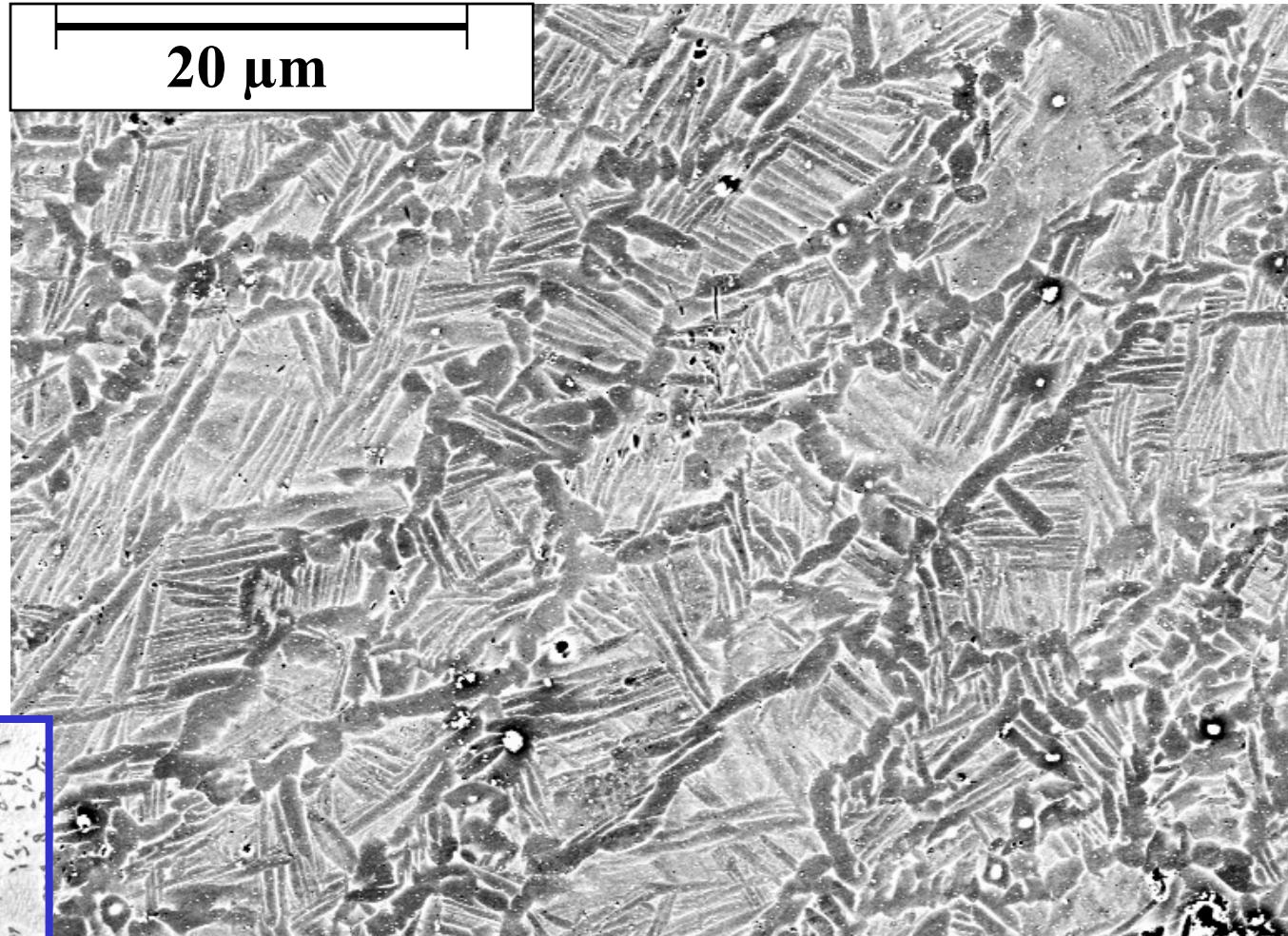


BEI images of FSW in Ti64

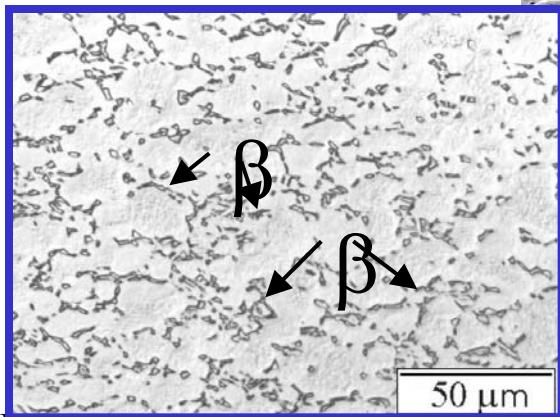




Stir Zone (Nugget) Microstructure



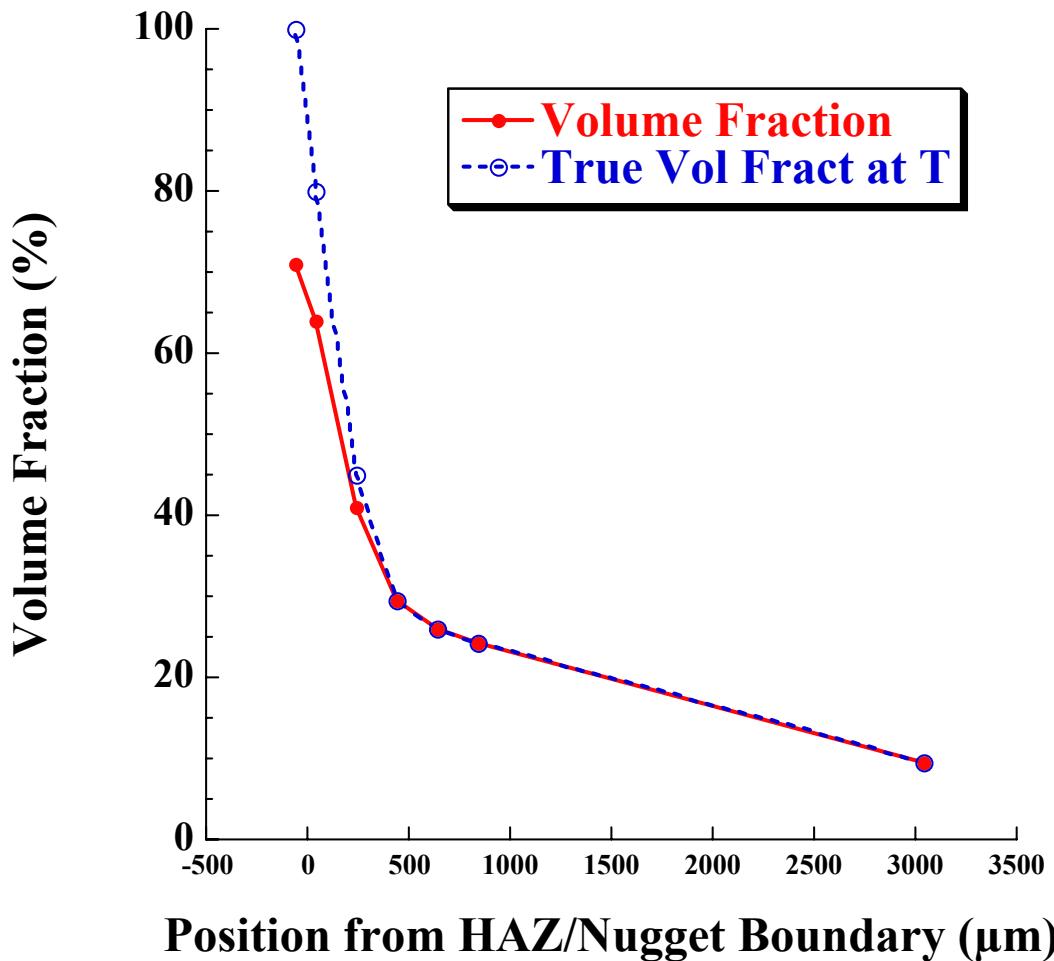
Base metal



Nugget

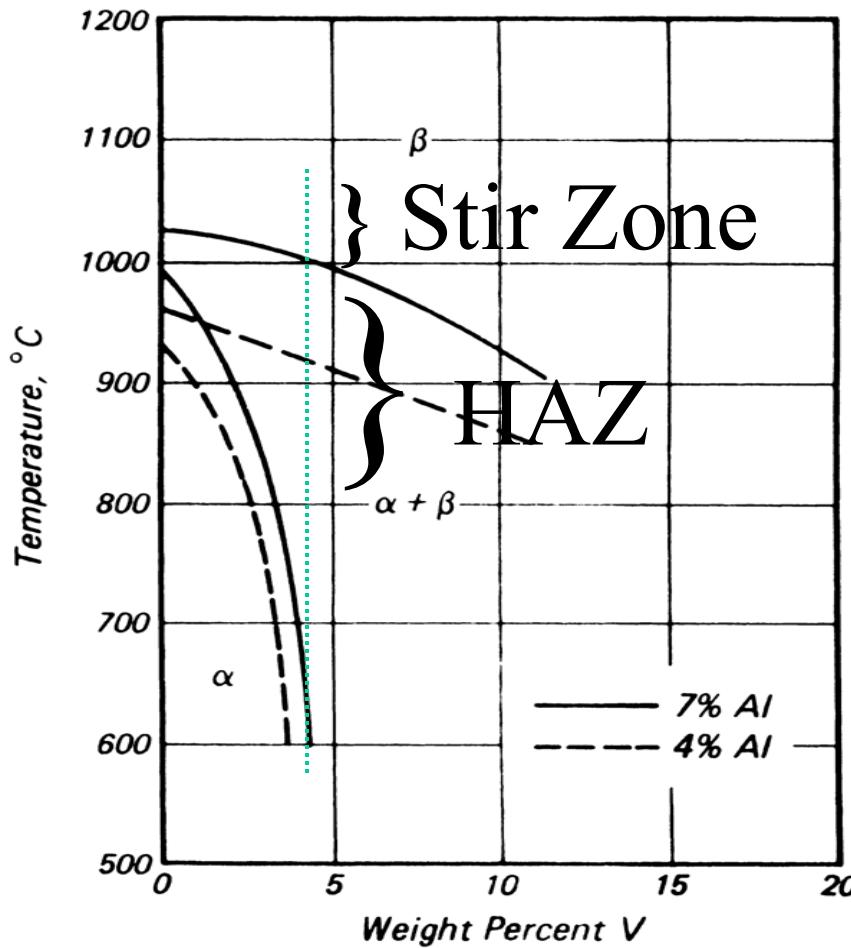


Transformed β volume fraction versus position





Vertical section in Ti-Al-V Phase Diagram





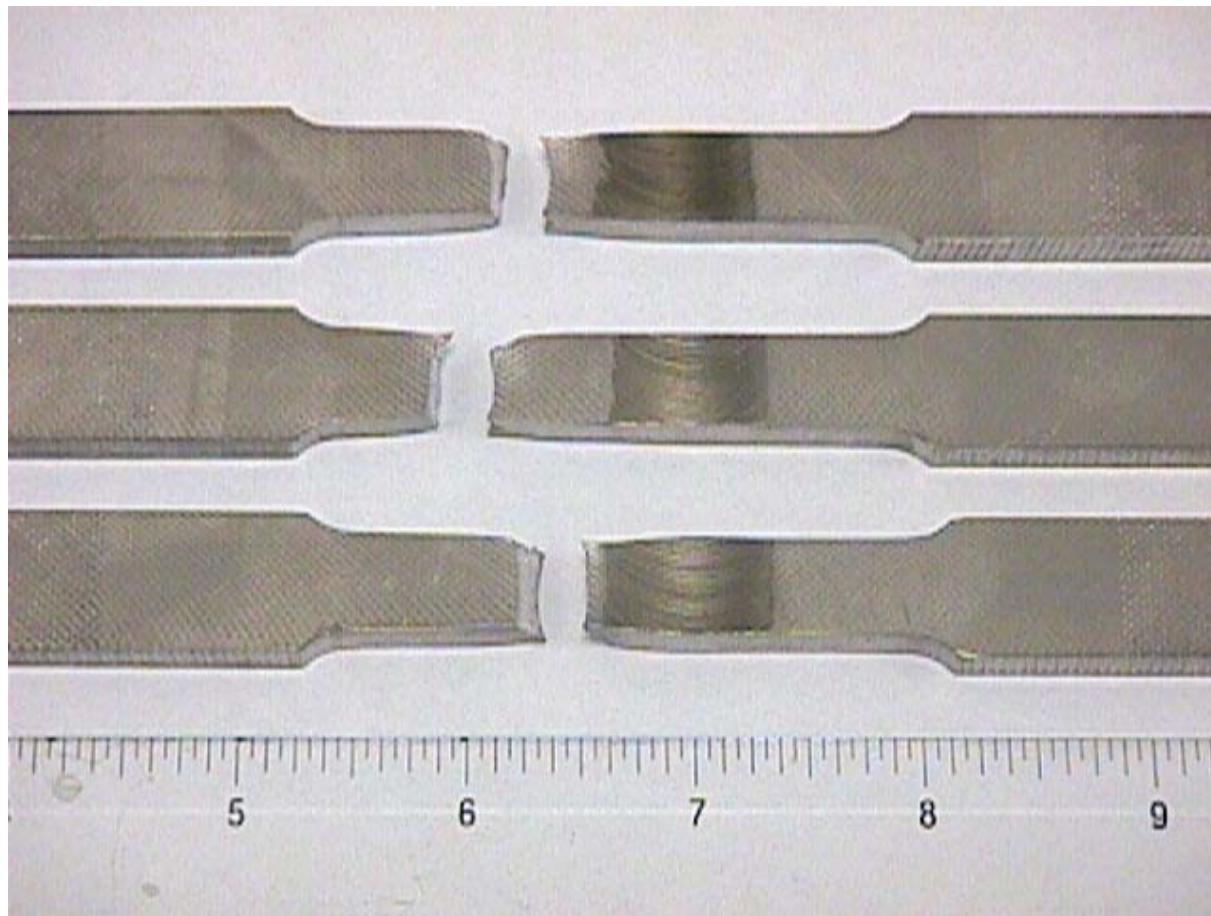
Results - Bend Test



$$\varepsilon > 12\%$$



Ti64: Tensile Test Specimens





Tensile Properties: Ti-6Al-4V

- Yield Strength: (MPa)
- Tensile Strength: (MPa)
- % Elongation:
- Failure Location:

| | <u>Base Metal</u> | <u>FSW</u> |
|---------------------------|-------------------|------------|
| • Yield Strength: (MPa) | 895 | 912 |
| • Tensile Strength: (MPa) | 957 | 1012 |
| • % Elongation: | 12.7 | 12.7(0.9) |
| • Failure Location: | NA | BASE |



Summary

- BM was equiaxed α with gb β
- % prior β in HAZ increased with decreasing distance from stir zone
- Stir zone contains acicular α in fine prior β grain size
- Weld tensile tests exhibit excellent joint efficiency and ductility
- FSW of Ti alloys is feasible



Research Areas

- Research Gaps
 - Need an Al alloy that is friction stir weldable and has all the good mechanical properties !!!!
 - How do you make the HAZ of ppt hardened Al alloy less corrosion susceptible?
 - A Model that will predict FSW properties for all Al alloys without extensive testing
 - Need a good FSW tool for Ti alloys